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Technical Letter
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Engineering and Design
OPERATION OF RESERVOIR SYSTEMS

1. Purpose

This engineer technical letter (ETL) presents field water-control managers a new tool for developing and evaluating reservoir system water control plans. This ETL expands the information on water-control analysis techniques presented in Chapter 6 of EM 1110-2-3600. A new software optimization package for reservoir system analysis is presented.

2. Applicability

This ETL applies to all HQUSACE elements, major subordinate commands, districts, laboratories, and field operating activities (FOA) where it is necessary to perform reservoir system analysis. The primary expected application is for the determination of reservoir water control plans.

3. References

References and additional sources of information are listed in Appendix A.

4. Reservoir Analysis Models

A brief description of computer programs for reservoir analysis is provided in Appendix C of EM 1110-2-1701. The models are listed as either flow-duration or sequential streamflow, plus one hybrid. A Hydrologic Engineering Center model review (HEC 1991a) provides a "...literature-review-based assessment of the state-of-the-art of modeling and analysis approaches for evaluating multiple-purpose reservoir system operations." Models, in this report, are categorized as descriptive simulation, prescriptive optimization, or hybrid simulation and optimization models. To date, most of the Corps' analyses have been performed with sequential streamflow (descriptive simulation) using one of the generalized models, or a specialized model for the system.

5. Descriptive Reservoir Simulation

a. Methods. Reservoir simulation is performed by repeatedly solving the storage equation for a reservoir *(inflow minus outflow equals change in storage)*. The simulation is descriptive because the system and its output requirements are all specified, e.g., the sequence of flow data, storage allocation, and project demands, priorities, and constraints. Given this description of the system, the output is the reservoir releases and the resulting reservoir storage and downstream flows. Chapter 5 of EM 1110-2-1701 provides a complete description of sequential streamflow routing for hydroelectric power. The same concepts and general procedures apply to other water conservation purposes. Reservoir simulation for flood control is presented in IHD Volume 7 (HEC 1976). The procedures outlined in Volume 7 were incorporated into the HEC-5 Simulation of Flood Control and Conservation Systems (HEC 1982). As mentioned in paragraph 4, the capabilities of HEC-5 and other computer models are summarized in EM 1110-2-1701.

b. Application. Reservoir simulation is a powerful tool because it allows the modeler to utilize the level of detail, and the available data, required to meet the objective(s) of the analysis. Sequential reservoir analysis can consider almost any physical process that could affect the reservoir inflow, outflow, and release determination. Typically, processes are defined as a functional relationship, or as a period-by-period input. The application approach is "case study," in that an operation policy, flow sequence, and system demands are specified and the simulation is performed to determine the result. Different "cases" are analyzed by changing the operation policy, demands, or other aspect, and running the simulation again. The simulation is *descriptive* of the expected reservoir operation, given the specified scenario.

c. Limitations. A disadvantage of this approach is the difficulty analyzing the large number of alternatives possible with a multiple-purpose, multiple-reservoir system. Additionally, most sequential simulations treat specified targets and demands as absolutes. The reservoirs release water to meet the specified demands as long as there is available water in the allocated water supply storage. The flood-control space is typically used in the same fashion, i.e., store floodwater if there is space available. While it is fairly easy to compare absolutes (e.g., flood control vs. conservation storage) it is harder to evaluate the trade-offs in operation policy.

6. Prescriptive Reservoir Optimization

a. Prescriptive vs. descriptive. A *descriptive* tool answers the question “How would the system perform if we followed this policy or set of priorities?” (HEC 1992a). A *prescriptive* tool is used to answer the question “How should we operate the system if we accept this definition of the goals of, and constraints on system operation?” (ibid). A prescriptive tool generates iteratively the alternative policies to be considered and evaluates the feasibility of each with a built-in simulation model. It quantifies the efficiency of each feasible alternative using a formal definition of operation goals and objectives. Finally, after evaluating all alternatives, it identifies the best policy. Examples of prescriptive tools are linear-programming, nonlinear-programming, and dynamic-programming models.

b. HEC-Prescriptive Reservoir Model. HEC has developed and applied a Prescriptive Reservoir Model (HEC-PRM) to analyze the operation of the Missouri and Columbia River Systems (*see*: HEC 1991c, 1991d, 1992a, and 1993 *in paragraph 3, Appendix A*). In HEC-PRM, a reservoir system is represented as a network of arcs connected at nodes. The arcs represent any facility for the transfer of water, both in space and time. The nodes represent reservoirs or other locations where flow is required or evaluated. The value of water in the system is defined in terms of penalties for flow, or water in storage, being too high or too low. The allocation of water in space and time is treated as a Minimum-cost Network-flow Problem. A more complete HEC-PRM description is provided in Appendix B.

c. Penalty functions. The penalty functions for flow, or water in storage, are developed for each project purpose, at each location, for each month of the year. The single-purpose penalty functions are then combined into composite functions at each location for each month of the year. The resulting combined functions are then edited, or smoothed, to yield a piecewise-linear convex function for the network solution. The requirements and general procedure are described in paragraph 5, Appendix B.

7. Data Requirements for HEC-PRM

There are three sets of data required for the model: hydrologic data, penalty data, and reservoir system data (HEC 1993, paragraph 2, Appendix A). Additional hydropower data may be required for reservoirs with significant pool variation.

a. Hydrologic data. The program requires flow data in the same units as storage data. Applications to date have used thousands of acre-feet per month. Flow data are input for upstream reservoir inflow and the incremental area inflow for downstream locations. While HEC-PRM allows the user to define a second hydrograph to define fixed depletions and an evaporation rate per month, the applications to date have made these types of adjustments to the input flow data. The data are read from an HEC-DSS file (HEC 1987b). The HEC-DSS utility programs provide for importing data from other files, and for manipulating the data to develop the required input to HEC-PRM.

b. Penalty data. This is the critical input for the HEC-PRM program. The program goal is to determine the reservoir operation that minimizes the total penalty for the simulation period. Obviously, there must be acceptance of the penalty values determined for each purpose in order to accept the resulting reservoir operation. The program summary (Appendix B) provides a description of typical penalty functions. For each node and month, the individual penalty functions are summed into composite penalty functions and they are stored in HEC-DSS. A utility program has been developed to read the composite functions from an HEC-DSS file and develop the convex, piecewise linear representation required by PRM. The utility provides a graphical display of the original and edited function, and allows the user to select the number of linear elements and to adjust the function values. An error value is displayed showing the relative mean deviation of the computed function from the input composite function.

c. Reservoir system data. The reservoir system data define the reservoir storages, the downstream connectivity, and the record path names to read the flow and penalty data from HEC-DSS. Minimum and maximum constraints on reservoir storage and channel flow are also defined. There is no routing in the model, so time-steps must be large enough for the flow to pass through the system within one time-step. Monthly data have been used. The reservoir data are defined in an ASCII file, with an input structure similar to other HEC programs. The HEC-PRM User's Manual (HEC 1993) provides the input requirements and formats.

d. Reservoir power data. When power reservoirs have a significant pool variation, hydropower capability and required hydropower releases depend on reservoir pool level. For specified reservoir storage values, a family of power capacity and hydropower penalty curves can be defined and stored in an HEC-DSS file. The hydropower penalty is assigned to a hydro-release link only. HEC-PRM can cycle to adjust storage, based on estimated outflow, in order to obtain the appropriate capacity and penalty values. This approach was used in the Columbia River System model (HEC 1993, paragraph 3, Appendix A).

8. HEC-PRM Output

a. Output tables. The primary output for the model is reservoir storage and outflow, and the total flow at each node, all written to an HEC-DSS file. Additionally, the program can compute reservoir elevation and energy production, if the conversion data are provided. A total system penalty value is computed based on the edited composite penalty functions; however the post-processor also computes the individual penalties for every purpose and sums them for each location. The time-series penalty data are also written to the output DSS file. A utility program has been developed to produce output tables from the results written to a DSS file. The utility can produce a variety of pre-defined and user-defined output tables of reservoir and node data, over time, or annual summaries. The utility also provides a graphical display of time-series data stored in the DSS file. Additionally, data written to HEC-DSS can be displayed with computer program DSPLAY (HEC 1987b).

b. Output interpretation. While standard tables of information on reservoir operation and the resulting penalty values can be produced, *the basis for reservoir release decisions must be inferred from the operation.* The operation results produce the minimum total penalty. The question is "How do we operate the real system to achieve the maximum benefit?" The HEC-PRM results must be analyzed and interpreted to formulate an operation plan. The output utility can provide duration and statistical data and plots, for any specified period and season, to facilitate output analysis. The derived operation plan could then be "tested" with a more detailed reservoir simulation. At this time, there has been limited application and only one systematic processing of preliminary output has been documented (HEC 1992b).

9. HEC-PRM Limitations

a. New software. Because this is a new reservoir system program, there has been limited application. The program is available and producing reasonable results, judging by the comparison between MRD simulation model and HEC-PRM results for a "normal" flow period. However, the results were not similar for a critical period analysis.

b. Limited simulation capabilities. As with most optimization models, the simulation aspects of the model are limited. Continuity is maintained. Specified maximum and minimum storage and flow constraints are observed. Hydropower capability can reflect variation in pool level. There is no routing in the simulation; therefore, applications are limited to large time-steps, e.g., monthly data.

c. Inferred operation policy. The basis for the period-by-period operation is hidden from the modeler. The results must be analyzed to develop insight into the operation policy that would produce similar results. The limited experience to date makes it difficult to specify the analysis strategy to use to develop an operation plan. Ongoing applications and analyses will give better insight in the near future.

FOR THE DIRECTOR OF CIVIL WORKS:

2 Appendices
APP A - References
APP B - Prescriptive Reservoir Model

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